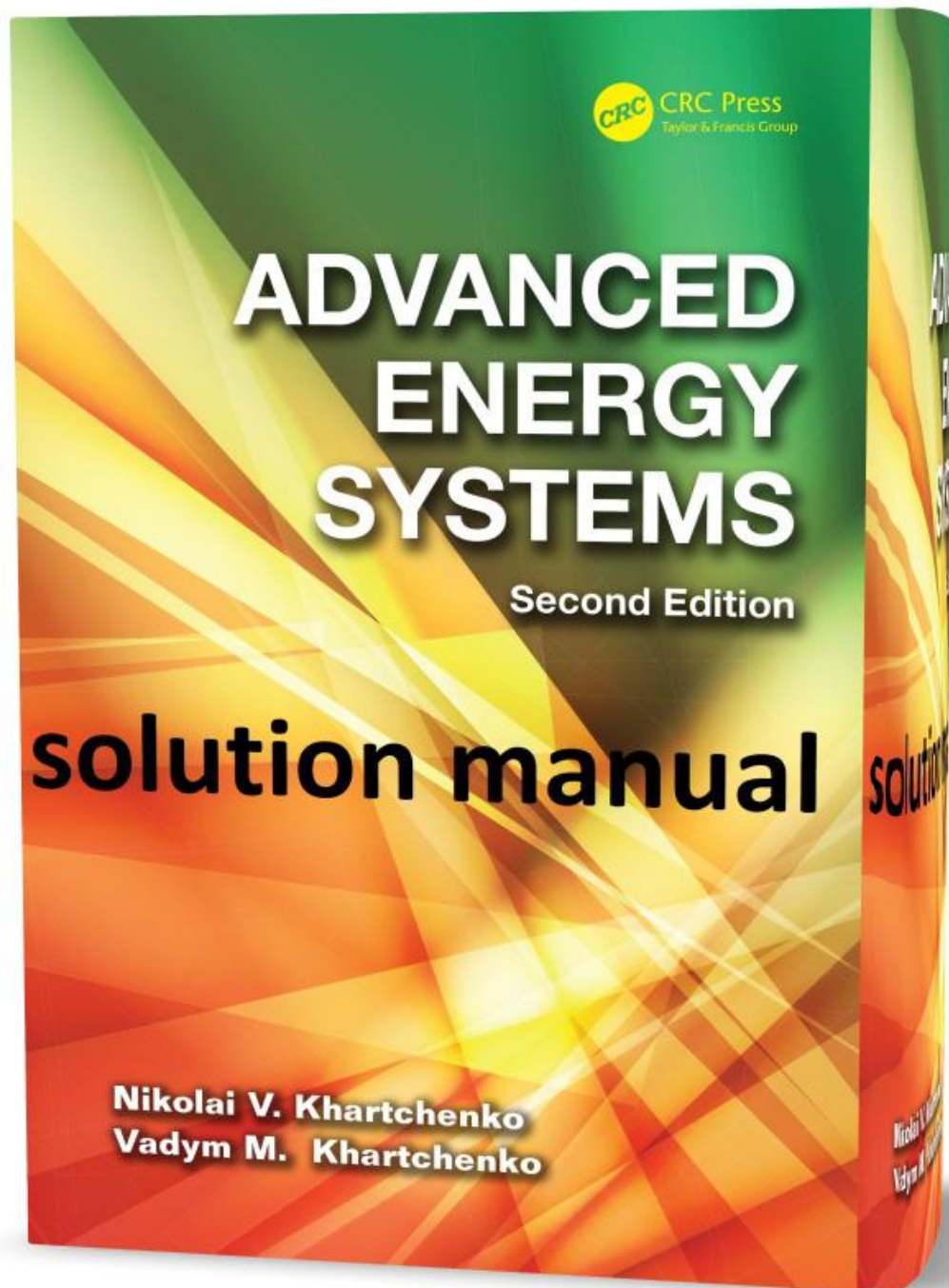


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SOLUTIONS MANUAL FOR

ADVANCED ENERGY SYSTEMS

SECOND EDITION

_____ by _____

Nikolai V. Khartchenko
Vadym M. Kharchenko



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Problem 1.1

An air stream of 0.6 kg/s is heated at constant pressure of 1.5 MPa from 620 K to 930 K. Calculate the rate: (i) the rate of work of volume change, (ii) the rate of heat addition, (iii) the rates of change in internal energy and the enthalpy of the air.

Given:

Air mass flow $m = 0.6$ kg/s; air pressure $p = 1.5$ MPa; air initial and final temperatures: $T_1 = 620$ K and $T_2 = 930$ K. For the air: gas constant $R = 0.287$ kJ/kgK, isentropic exponent $k = 1.4$, isochoric specific heat $c_v = 0.718$ kJ/kgK and isobaric specific heat $c_p = 1.005$ J/kgK.

Calculate:

Rate of work of volume change W , heat input rate Q , rates of internal energy change ΔU and enthalpy change ΔH of the air. Set up the energy flow balance for the isobaric heat addition process.

The isobaric heat addition process. with an ideal gas is shown in Figure 1.1.

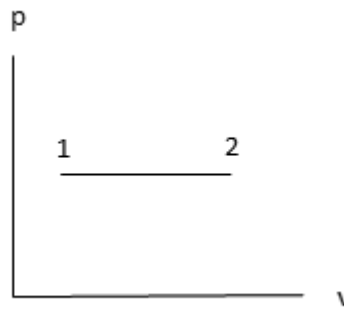


Figure 1.1. P - v diagram of an isobaric heat addition process with ideal gas

Solution:

1. Specific volume of the air at initial and final states, respectively

$$v_1 = R v_1 / p = 0.287 \text{ kJ/kgK} * 620 \text{ K} / 1500 \text{ kPa} = 0.1186 \text{ m}^3/\text{kg}$$

$$v_2 = v_1 T_2 / T_1 = 0.1186 * 930 / 620 = 0.1779 \text{ m}^3/\text{kg}$$

2. Rate of work of volume change

$$W = m p (v_2 - v_1) = 0.6 \text{ kg/s} * 1500 \text{ kPa} * (0.1779 - 0.1186) \text{ m}^3/\text{kg} = 53.38 \text{ kJ/s}$$

3. Rate of heat addition

$$Q = m c_p (T_2 - T_1) = 0.6 \text{ kg/s} * 1.005 \text{ kJ/kgK} * (930 - 620) \text{ K} = 186.93 \text{ kJ/s}$$

4. Rates of change in internal energy and enthalpy of the air

$$\Delta U = m c_v (T_2 - T_1) = 0.6 \text{ kg/s} * 0.718 \text{ kJ/kgK} * (930 - 620) = 133.55 \text{ kJ/s}$$

$$\Delta H = m c_p (T_2 - T_1) = Q = 186.93 \text{ kJ/s}.$$

5. Based on the first law of thermodynamics, the process energy flow balance

$$Q = W + \Delta U: 186.93 \text{ kJ/s} = 53.38 \text{ kJ/s} + 133.55 \text{ kJ/s}.$$

Answer:

$$W = 53.38 \text{ kJ/s}, Q = 186.93 \text{ kJ/s}, \Delta H = 186.93 \text{ kJ/s}.$$

Problem 1.2

A gas turbine compressor compresses 235 kg/s of air from $p_1 = 1$ bar and $T_1 = 300$ K to $p_2 = 17$ bars in an isentropic process. Calculate (i) the air final temperature, (ii) the power input to the compressor, (iii) the rates of change in internal energy and enthalpy of the air. For the air: $k = 1.4$, $c_v = 0.718$ kJ/kgK and $c_p = 1.005$ kJ/kgK.

Given:

Mass flow rate of the air $\dot{m} = 235 \text{ kg/s}$, initial state: $p_1 = 1 \text{ bar}$ and $T_1 = 300 \text{ K}$, final pressure $p_2 = 17 \text{ bars}$.

Calculate:

Air final temperature T_2 , rate of compressor shaft work $\dot{W}_c$, rates of change in internal energy and enthalpy of the air, ΔU and ΔH .

The isentropic compression process with an ideal gas is shown in Figure 1.2.

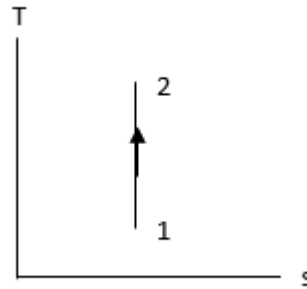


Figure 1.2. $T - s$ diagram of an isentropic compression process with ideal gas

Solution:

1. Air final temperature

$$T_2 = T_1 (p_2 / p_1)^{(k-1)/k} = 300 * (17/1)^{(1.4-1)/1.4} = 674 \text{ K}$$

2. Power input to the compressor, i.e., rate of the compressor shaft work

$$\dot{W}_c = \dot{m} c_p (T_1 - T_2) = 235 * 1.005 * (300 - 674) = -163516 \text{ kJ/s}$$

3. Rates of change in internal energy and enthalpy of the air

$$\Delta U = \dot{m} c_v (T_2 - T_1) = 235 * 0.718 * (674 - 300) = 116820 \text{ kJ/s}$$

$$\Delta H = \dot{m} c_p (T_2 - T_1) = 235 * 1.005 * (674 - 300) = 163516 \text{ kJ/s}$$

4. Energy flow balance for the process per unit time

$$\text{For the isentropic process } Q = 0 \text{ and } \dot{W}_c = -\Delta H: -163516 = -163516.$$

Answer: $T_2 = 674 \text{ K}$, $\dot{W}_c = -163516 \text{ kJ/s}$, $\Delta U = 116820 \text{ kJ/s}$ and $\Delta H = 163516 \text{ kJ/s}$.

Problem 1.3

An arbitrary heat engine is operating with the average heat addition and heat rejection temperatures $T_{in,1}$ and $T_{out,1}$ of 600 K and 360 K, respectively. The thermal efficiency of the cycle should be increased by 25% (i) by increasing the heat addition temperature or (ii) by decreasing the heat rejection temperature. Determine the required temperatures (i) $T_{in,2}$ and (ii) $T_{out,2}$.

Given:

Heat addition and heat rejection temperatures $T_{in,1} = 600 \text{ K}$ and $T_{out,1} = 360 \text{ K}$.

Thermal efficiency of the cycle should be increased by 25% by changing these temperatures.

Calculate:

Required temperatures (i) $T_{in,2}$ and (ii) $T_{out,2}$.

Refer to Figure 1.4 in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Initial thermal efficiency of the cycle

$$\eta_{th,1} = 1 - T_{out,1} / T_{in,1} = 1 - 360/600 = 0.4$$

2. Thermal efficiency is increasing from $\eta_{th,1} = 0.4$ to $\eta_{th,2} = 0.5$

(i) If the heat addition temperature increases from $T_{in,1}$ of 600 K to

$$T_{in,2} = T_{out,1} / (1 - \eta_{th,2}) = 360 / (1 - 0.5) = 720 \text{ K or}$$

(ii) If the heat rejection temperature decreases from $T_{out,1}$ of 360 K to

$$T_{out,2} = T_{in,1} * (1 - \eta_{th,2}) = 600 / (1 - 0.5) = 300 \text{ K.}$$

Hence, the cycle thermal efficiency η_{th} increases if the temperature difference $T_1 - T_2$ increases. *Answer:* $T_{in,2} = 720 \text{ K}$ and $T_{out,2} = 300 \text{ K}$.

Problem 1.4

A steam turbine is operating at a steam flow rate of 550 kg/s with an enthalpy of live steam h_1 of 3670 kJ/kg and enthalpy of exhaust steam h_2 of 2010 kJ/kg. The condensate enthalpy h_c at the condenser outlet is 140 kJ/kg. Calculate (i) the power output of the steam turbine, (ii) the rate of heat rejection in the condenser, and (iii) the required cooling water flow in the condenser, where its temperature increases by $\Delta T_{cw} = 11 \text{ K}$. Specific heat of the water is 4.19 kJ/kgK.

Given:

Steam flow rate $m = 550 \text{ kg/s}$. Enthalpies of live steam $h_1 = 3670 \text{ kJ/kg}$, exhaust steam $h_2 = 2010 \text{ kJ/kg}$ and condensate $h_c = 140 \text{ kJ/kg}$. Temperature of cooling water increases in condenser by $\Delta T_{cw} = 11 \text{ K}$.

Calculate:

Turbine power output P_t , heat rejection rate in the condenser Q_c , cooling water requirements m_{cw} .

Solution:

1. Power output of the steam turbine

$$P_t = m (h_1 - h_2) = 550 \text{ kg/s} * (3670 - 2010) \text{ kJ/kg} = 913 \text{ MW}$$

2. Rate of heat rejection in the condenser

$$Q_c = m (h_2 - h_c) = 550 \text{ kg/s} * (2010 - 140) \text{ kJ/kg} = 1028.5 \text{ MJ/s}$$

3. Flow rate of the cooling water

$$m_{cw} = Q_c / (c_p \Delta T_{cw}) = 1028500 \text{ kJ/s} / (4.19 \text{ kJ/kgK} * 11 \text{ K}) = 22315 \text{ kg/s} = 80330 \text{ t/h.}$$

Answer:

$$P_t = 913 \text{ MW}, Q_c = 1028.5 \text{ MJ/s}, m_{cw} = 22315 \text{ kg/s} = 80330 \text{ t/h.}$$

Problem 1.5

A two-layer 24 m^2 plane wall consists of a 250 mm thick inner concrete layer with thermal conductivity k_1 of 2 W/m K and a 80 mm thick outer insulation with k_2 of 0.04 W/m K. The temperatures of wall inner and outer surfaces are: $t_1 = 28^\circ\text{C}$ and $t_3 = -9^\circ\text{C}$. Calculate (i) the rate of heat transfer and (ii) the temperature t_2 of the wall intermediate surface.

Given:

Wall surface area $A = 24 \text{ m}^2$, thickness of inner and outer layers $\delta_1 = 250 \text{ mm}$ and $\delta_2 = 80 \text{ mm}$, their thermal conductivity $k_1 = 2 \text{ W/m K}$ and $k_2 = 0.04 \text{ W/m K}$. Temperatures of inner and outer surfaces $t_1 = 28^\circ\text{C}$ and $t_3 = -9^\circ\text{C}$.

Calculate:

Rate of heat transfer Q and temperature of the wall intermediate surface t_2 .

Refer to Figure 1.6 in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Thermal resistance of the 2-layer wall

$$R_w = R_1 + R_2 = \delta_1 / k_1 + \delta_2 / k_2 = 0.25/2 + 0.08/0.04 = 0.125 + 2 = 2.125 \text{ m}^2\text{K/W}$$

2. Rate of heat transfer

$$Q = A (t_1 - t_3) / R_w = 24 * [28 - (-12)] / 2.125 = 417.9 \text{ W}$$

3. Temperature of the wall intermediate surface

$$t_2 = t_1 - R_1 Q / A = 28 - 0.125 * 417.9 / 24 = 25.82^\circ\text{C}$$

Answer:

$$Q = 417.9 \text{ W and } t_2 = 25.82^\circ\text{C}.$$

Problem 1.6

Water flows at a velocity of 1.2 m/s in a tube with a diameter of 50 mm and a length L of 16 m. The mean temperature of water is 30°C and that of tube surface is 39°C.

Calculate (i) the heat transfer coefficient and (ii) the rate of heat transfer from tube to the fluid. Physical properties of water at 30°C are: $k = 0.614 \text{ W/mK}$, $\nu = 0.801 * 10^{-6} \text{ m}^2/\text{s}$, $Pr = 5.43$.

Given:

Water velocity $u = 1.2 \text{ m/s}$, tube diameter $d = 50 \text{ mm}$ and length $L = 16 \text{ m}$. Water and tube surface temperatures: $t_f = 30^\circ\text{C}$ and $t_w = 39^\circ\text{C}$. Properties of water at 30°C: $k = 0.614 \text{ W/mK}$, $\nu = 0.801 * 10^{-6} \text{ m}^2/\text{s}$, $Pr = 5.43$.

Calculate:

Heat transfer coefficient h and rate of heat transfer Q .

Solution:

1. Reynolds number $Re = u d / \nu$

$$Re = u d / \nu = 1.2 * 0.05 / (0.801 * 10^{-6}) = 74906.$$

As $Re > 10,000$, the fluid flow is turbulent.

2. Nusselt number

$$Nu = 0.023 Re^{0.8} Pr^{0.4} = 0.023 * (74906)^{0.8} * 5.43^{0.4} = 359$$

3. Heat transfer coefficient

$$h = Nu k / d = 359 * 0.614 / 0.05 = 4408 \text{ W/(m}^2\text{K)}$$

4. Rate of heat transfer

$$Q = \pi d L h (t_w - t_f) = \pi * 0.05 * 16 * 4408 * (39 - 30) = 99706 \text{ W}.$$

Answer: $h = 4408 \text{ W/(m}^2\text{K)}$, $Q = 99706 \text{ W}$.

Problem 1.7

Calculate the net rate of energy exchange by thermal radiation in a system consisting of two large parallel plane surfaces 1 and 2 with a surface area of $A = 4 \text{ m}^2$ each, temperatures T_1 of 550 K and T_2 of 430 K, and emissivities ϵ_1 of 0.3 and ϵ_2 of 0.8.

Assume that the distance between the two plane surfaces is small compared to their dimensions.

Given:

Two parallel grey planes. Plane surface area $A = 4 \text{ m}^2$, temperatures $T_1 = 550 \text{ K}$ and $T_2 = 430 \text{ K}$, and emissivities ϵ_1 of 0.3 and ϵ_2 of 0.8

Calculate:

Net rate Q_{12} of energy exchange by thermal radiation. Refer to Figure 1.8a in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Effective emissivity of the system

$$\epsilon_{\text{eff}} = (1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1} = (1/0.3 + 1/0.8 - 1)^{-1} = 0.279$$

2. Net rate of radiation energy exchange between planes 1 and 2

$$Q_{12} = \epsilon_{\text{eff}} A \sigma (T_1^4 - T_2^4) = 0.279 \times 4 \times 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \times (550^4 - 430^4) \text{ K}^4$$
$$Q_{12} = 3628 \text{ W}$$

Answer:

$$Q_{12} = 3628 \text{ W.}$$

Problem 1.8

Calculate the net rate of energy exchange by thermal radiation between a grey convex body 1 and its grey enclosure 2. The surface area of the convex body is A_1 of 0.8 m^2 , its temperature T_1 is 410 K and emissivity ϵ_1 is 0.6 . The enclosure has a surface area A_2 of 1.6 m^2 , temperature T_2 of 330 K and emissivity ϵ_2 of 0.9 .

Given:

Grey convex body 1: A_1 of 0.8 m^2 , T_1 is 410 K , ϵ_1 is 0.6

Grey enclosure 2: A_2 of 1.6 m^2 , T_2 of 330 K and ϵ_2 of 0.9

Calculate:

Net rate Q_{12} of energy exchange by thermal radiation. Refer to Figure 1.8b in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Effective emissivity of the system

$$\epsilon_{\text{eff}} = [1/\epsilon_1 + (1/\epsilon_2 - 1) A_1/A_2]^{-1} = [(1/0.6 + 1/0.9 - 1) \times 0.8/1.6]^{-1} = 0.581$$

2. Net rate of energy exchange by thermal radiation between body and its enclosure

$$Q_{12} = \epsilon_{\text{eff}} A_1 \sigma (T_1^4 - T_2^4) = 0.581 \times 0.8 \text{ m}^2 \times 5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \times (410^4 - 330^4) \text{ K}^4$$
$$Q_{12} = 432.2 \text{ W.}$$

Answer:

$$Q_{12} = 432.2 \text{ W.}$$

Problem 1.9

For a counter-flow water-water heat exchanger, the mass flow rates of hot and cold fluids are $m_h = 0.24 \text{ kg/s}$ and $m_c = 0.2 \text{ kg/s}$, the overall heat transfer coefficient is $U = 1700 \text{ W/m}^2\text{K}$, the hot fluid temperatures are $t_{hi} = 66^\circ\text{C}$ (inlet), $t_{he} = 48^\circ\text{C}$ (exit) and hot fluid inlet temperature is $t_{ci} = 19^\circ\text{C}$. The specific heat of hot and cold fluids c_p is 4.19 kJ/kgK . Calculate (i) the heat transfer rate, (ii) the exit temperature of cold fluid, and (iii) the heat transfer surface area.

Given:

Counter-flow heat exchanger. Overall heat transfer coefficient is $U = 1700 \text{ W/m}^2\text{K}$.

Hot fluid: $m_h = 0.24 \text{ kg/s}$, $t_{hi} = 66^\circ\text{C}$, $t_{he} = 48^\circ\text{C}$. Cold fluid: $m_c = 0.2 \text{ kg/s}$, $t_{ci} = 19^\circ\text{C}$.

Calculate:

Heat flow rate Q , exit temperature of cold fluid t_{ce} and heat transfer surface area A . Refer to Figures 1.9a and b in the book "Advanced Energy Systems", 2nd ed.

Solution:

1. Heat transfer rate

$$Q = m_h c_p (t_{hi} - t_{he}) = 0.24 \text{ kg/s} \times 4.19 \text{ kJ/kgK} \times (66 - 48) \text{ K} = 18.1 \text{ kJ/s}$$

2. Exit temperature of the cold fluid

$$t_{ce} = t_{ci} + Q / (m_c c_p) = 19^\circ\text{C} + 18.1 \text{ kJ/s} / (0.2 \text{ kg/s} \times 4.19 \text{ kJ/kgK}) = 40.6^\circ\text{C}$$

3. Mean temperature difference between hot and cold fluids (approximately)

$$\Delta T_m = [(t_{hi} - t_{ce}) + (t_{he} - t_{ci})]/2 = [(66 - 40.6) + (48 - 19)]/2 = 27.2 \text{ K}$$

4. Heat transfer surface area of the heat exchanger

$$A = Q / (U \Delta T_m) = 18.1 \text{ kJ/s} / (1.7 \text{ kW/m}^2\text{K} * 27.2 \text{ K}) = 0.391 \text{ m}^2$$

Answer:

$$Q = 18.1 \text{ kJ/s}, t_{ce} = 40.6^\circ\text{C}, A = 0.391 \text{ m}^2.$$

Problem 1.10

Water flows with a velocity of 1.3 m/s in a 25 m long hydraulically smooth pipe with a diameter of 40 mm. The water temperature is 20°C. A pump is used to raise the water pressure by 3 bars. Calculate (i) the volumetric flow rate of water, (ii) the pressure loss in the pipe, and (iii) the power required to drive the pump if its efficiency is 0.86.

Physical properties of water at 20°C: Density $\rho = 998 \text{ kg/m}^3$, kinematic viscosity $\nu = 1.004 \times 10^{-6} \text{ m}^2/\text{s}$.

Given: pipe $d = 40 \text{ mm}$ and $L = 25 \text{ m}$, velocity $u = 1.3 \text{ m/s}$, $\Delta p_p = 3 \text{ bars}$,

Calculate: Water flow rate Q , pressure loss in the pipe Δp_{loss} , and power to drive the pump P_p .

Solution:

1. Volumetric flow rate of water

$$Q = u A = u \pi d^2/4 = 1.3 * \pi * 0.04^2/4 = 0.001634 \text{ m}^3/\text{s}$$

1. Reynolds number

$$Re = u d / \nu = 1.3 * 0.04 / (1.004 * 10^{-6}) = 51793.$$

As $Re > 10^4$, the water flow is turbulent.

2. The friction factor for turbulent flow with $Re < 10^5$ is given by

$$\lambda = 0.3164 / Re^{0.25} = 0.3164/51793^{0.25} = 0.021$$

3. Pressure loss in the pipe due to friction

$$\Delta p_{\text{loss}} = \lambda (L/d) \rho u^2 / 2 = 0.021 * (25/0.04) * 998 * 1.3^2/2 = 11068 \text{ Pa}$$

4. Power required to drive the pump

$$P_p = Q (\Delta p_p + \Delta p_{\text{loss}}) / \eta_p = 0.001634 \text{ m}^3/\text{s} * (3 * 10^5 + 11068) \text{ Pa} / 0.86 = 591 \text{ W}.$$

Answer:

$$Q = 0.001634 \text{ m}^3/\text{s}, \Delta p_{\text{loss}} = 11068 \text{ Pa}, P_p = 591 \text{ W}.$$

Problem 2.1

A bituminous coal has the following composition (in % by mass): carbon 80%, hydrogen 5%, oxygen 4%, ash 5% and moisture 6%.

Calculate: (a) the stoichiometric and actual air-fuel ratios for a 10% excess air in kg/kg, (b) the volumes of the constituents of the products of combustion, and (c) the mole fractions of the products of combustion. Ignore the air humidity, i.e. $\omega = 0$.

Given:

Coal ultimate analysis (in % by mass): C = 80%, H = 5%, O = 4%, A = 5%, M = 6%.

Excess air ratio $\lambda = 1.1$.

Calculate:

Stoichiometric and actual air-fuel ratios f_{st} and f_a , mole fractions of the products of combustion r_i .

Refer to Figure 2.1 in the book "Advanced Energy Systems", 2nd ed.

Solution:

Stoichiometric (theoretical, minimum) mass of oxygen per unit mass of fuel

$$m_{O_2} = 2.67C + 7.94 H - O = 2.67*0.8 + 7.94*0.05 - 0.04 = 2.49 \text{ kg/kg}$$

Stoichiometric and actual mass of dry combustion air in kg air per kg fuel

$$m_{a, st} = m_{O_2} / 0.232 = 2.49/0.232 = 10.745 \text{ kg/kg},$$
$$m_{a, act} = \lambda m_{a, t} = 1.1*10.745 = 11.82 \text{ kg/kg}$$

Stoichiometric (theoretical) and actual volume of combustion air

$$V_{a, st} = m_{a, st} / \rho_a = 10.745/1.293 = 8.31 \text{ m}^3 \text{ air per kg fuel}$$
$$V_a = m_{a, act} / \rho_a = 11.82/1.293 = 9.14 \text{ m}^3 \text{ air per kg fuel}$$

Density of a flue gas constituent, $\rho_i = M_i/V_M$, (where M_i = molar mass in kg/kmol and mole volume $V_M = 22.4 \text{ m}^3/\text{kmol}$). Hence,

$$\rho_{CO_2} = 44/22.4 = 1.977 \text{ kg/m}^3, \rho_{H_2O} = 18/22.4 = 0.804 \text{ kg/m}^3,$$
$$\rho_{SO_2} = 64/22.4 = 2.931 \text{ kg/m}^3, \rho_{N_2} = 28/22.4 = 1.257 \text{ kg/m}^3,$$
$$\rho_{O_2} = 32/22.4 = 1.429 \text{ kg/m}^3.$$

Stoichiometric (theoretical, minimum) volumes of flue gas constituents per kg fuel

Volume of carbon dioxide

$$V_{CO_2} = 3.67 C / \rho_{CO_2} = 3.67*0.8 / 1.977 = 1.485 \text{ m}^3 \text{ per kg fuel}$$

Actual volume of nitrogen

$$V_{N_2} = 0.79 V_a = 0.79*9.14 = 7.22 \text{ m}^3 \text{ per kg fuel}$$

Volume of oxygen ($\lambda = 1.1$, actual)

$$V_{O_2} = 0.232 (\lambda - 1) m_{a, act} / \rho_{O_2} = 0.232*(1.1 - 1)*11.82 / 1.429 = 0.19 \text{ m}^3 \text{ per kg fuel}$$

Volume of water vapor (actual)

$$V_{H_2O} = (8.94 H + M) / \rho_{H_2O} = (8.94*0.05 + 0.06) / 0.804 = 0.63 \text{ m}^3 \text{ per kg fuel}$$

Actual volume of wet flue gas

$$V_g = V_{CO_2} + V_{N_2} + V_{O_2} + V_{H_2O} = 1.485 + 7.22 + 0.19 + 0.63 = 9.53 \text{ m}^3 \text{ per kg fuel}$$

Mole fractions of the products of combustion

$$r_{CO_2} = V_{CO_2} / V_g = 1.485 / 9.53 = 0.15$$
$$r_{N_2} = V_{N_2} / V_g = 7.22 / 9.53 = 0.76$$
$$r_{O_2} = V_{O_2} / V_g = 0.19 / 9.53 = 0.02$$
$$r_{H_2O} = V_{H_2O} / V_g = 0.63 / 9.53 = 0.07$$